Timing drive analysis

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Design Analysis

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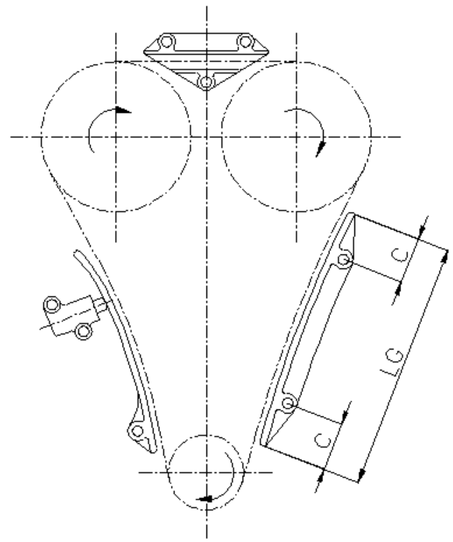
Agenda

- **Introduction**
- Chain drive
- Belt drive
- Gear drive
- Conclusions

Introduction – History (1)

- **Until 10 years ago timing drives were designed using rules of thumb developed over many years by engine designers and timing drive component suppliers**
  - maximum span length
  - minimum wrap angle
- **These guidelines were supplemented by**
  - rudimentary analysis
  - rig testing using constant speed input
- **Mostly this process led to**
  - conservative drive layouts
  - long development process
  - over-engineered components
- **Occasionally disasters occurred**
  - Failure to complete development process
  - Requiring radical redesign of whole engine
  - Warranty problems for life of engine



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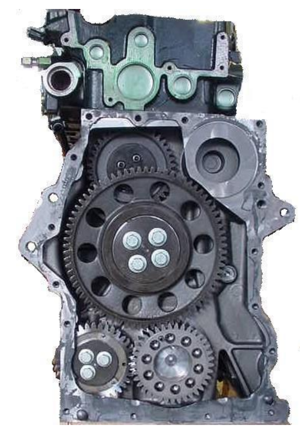
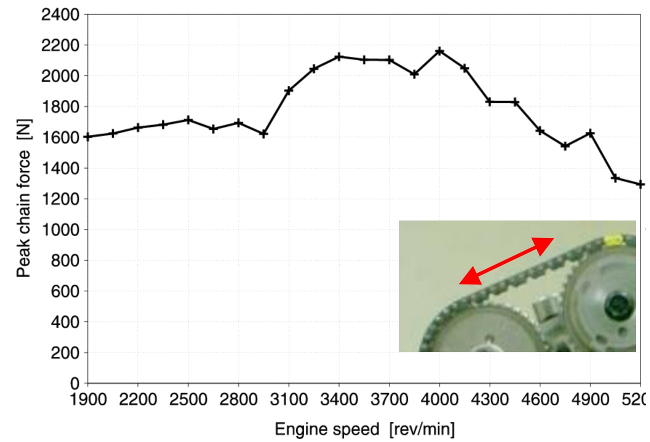
Introduction – History (2)

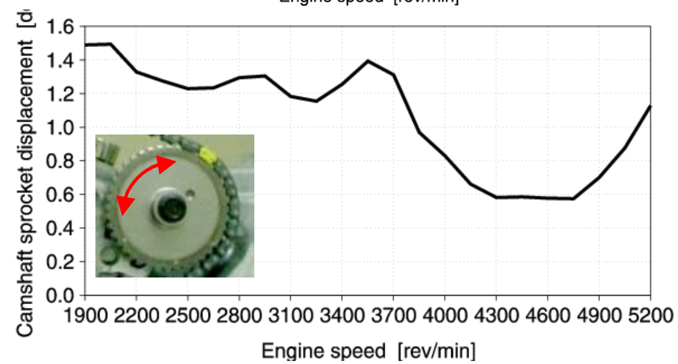
- **In the late 1990s change came from many directions**
- **Increased excitation from camshafts and crankshafts on passenger cars**
  - higher cylinder pressures from diesel engines and fuel pumps driven by timing chain
  - adoption of dual mass flywheels led to increased crank nose motion at low speed
  - higher engine speeds on some high performance gasoline engines
- **Adoption of overhead camshaft layout on heavy duty truck engines to drive injectors with required precision**
- **Increased need for low cost solutions in most market segments**
  - Reduce design/development costs/timescales
  - Reduce component/system costs
  - Reduce warranty costs
- **Wide-spread availability of computing power and development of hi-fidelity analysis tools such as VALDYN**

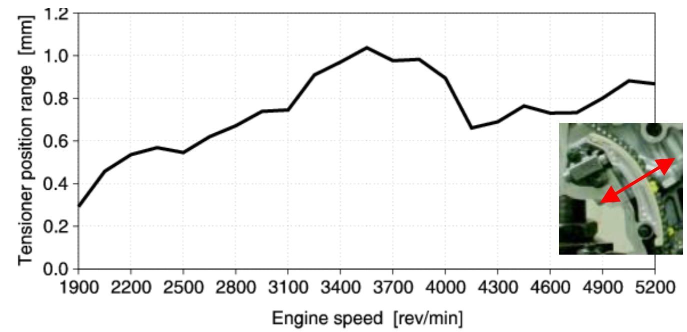


Introduction – History (3)

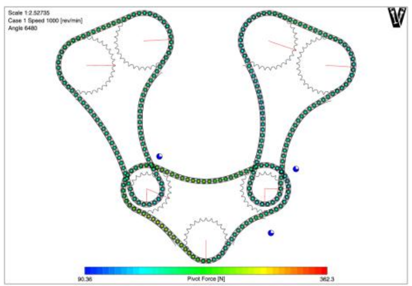
- **Use of VALDYN**
  - Software developed initially to investigate the failure of a balancer chain drive during development
  - Results gave much improved understanding of system dynamics and durability
  - Correlation with measured data by Ricardo and other users increased confidence in predictions
  - Gradually use of VALDYN became standard part of definitive design phase for timing drive and balancer drives
- **Timing drive design is now led by analysis**
  - Routine analysis at concept phase for chain drives
  - Analysis of belts and gears is slightly behind but Ricardo are ready
  - Analysis increasingly used for NVH studies
- **VALDYN is used by engine manufacturers and chain suppliers as well as Ricardo**

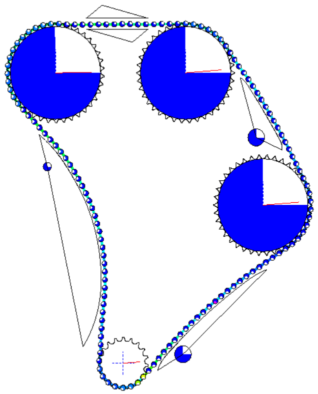




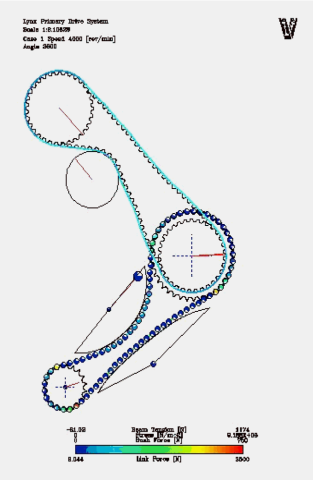


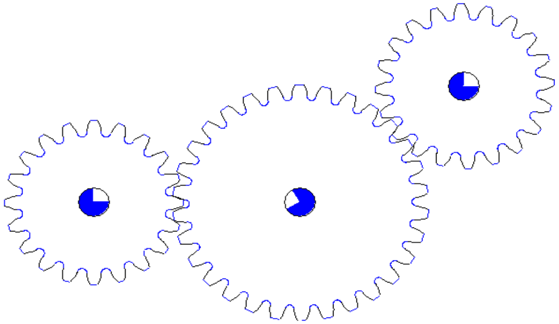
Introduction – Case studies





- **This presentation uses a series of case studies to illustrate**
  - the capabilities of VALDYN
  - the current experience base of Ricardo and other VALDYN users
  - the potential benefits of timing drive analysis
    - Improved understanding of system dynamics and component loading
    - Reduced costs
    - Reduced weight
    - Improved durability
    - Reduced noise





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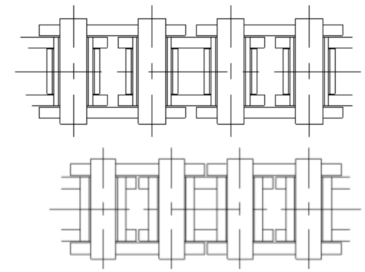
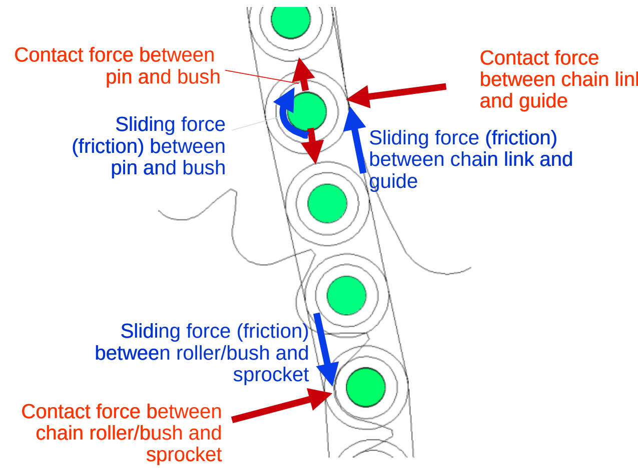
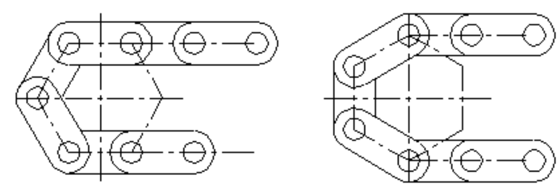
Chain drive – VALDYN capability (1)

- **VALDYN has the capability to model the following chain types and has a simple user interface**
  - Roller chain
  - Bush chain
  - Silent chain
  - Other special chains with novel designs
- **Each chain link is modelled as a separate mass**
  - connected to adjacent links by stiffness
  - connected to sprockets and guides by contact stiffness elements
- **The detailed geometry of the chain, sprockets and guides is modelled accurately**
- **Effects of polygon action and lateral chain vibration are captured**

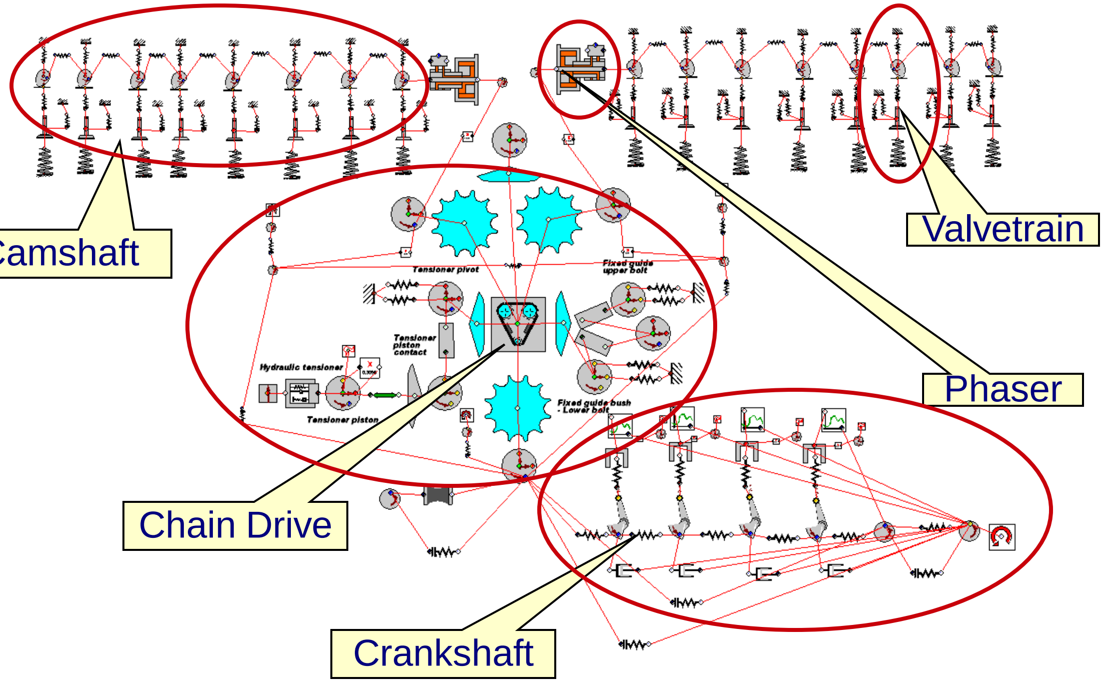




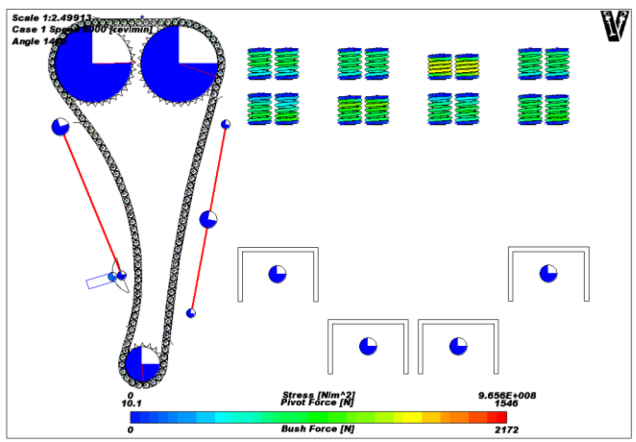


Chain drive – VALDYN capability (2)

- **There are special elements for modelling hydraulic tensioners and hydraulic vane phasers**
- **VALDYN is also capable of modelling dynamics of valve trains and rotational dynamics of crankshafts**
  - so coupled dynamics of the whole system can be studied



- **Animator included**

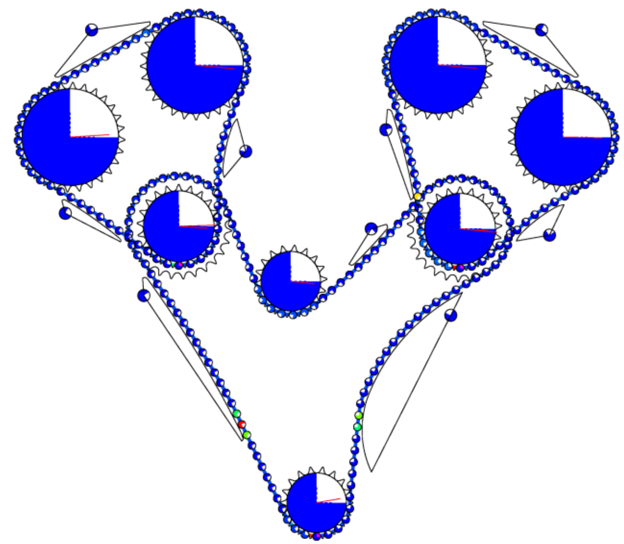


- **Co-simulation is possible**
  - With other Ricardo Software
  - With other programs

MATLAB
EASY5 Software for virtual system prototyping, simulation, and control.
NEW!

Chain drive – Case 1 – V6 drive analysis and redesign (1)

- **VALDYN was used to model the roller chain timing drive of a prototype V6 gasoline engine to**
  - ensure chain tension was lower than fatigue limit of chain specification
  - provide bearing loads for bearing durability analysis (front cam, idlers)
  - provide dynamic valve motion / timing for performance simulation
- **The VALDYN model was excited by**
  - measured crankshaft excitation
  - dynamic valve train model
- **Analysis runs predicted chain loads that exceeded the fatigue limit of the specified 8mm pitch chain**
- **Parametric studies looking at the tensioner and cam profile designs did not reduce the chain loads sufficiently**
- **Analysis was re-performed using a larger 9.525mm pitch chain with a higher fatigue limit and was assessed to be acceptable**



Chain drive – Case 1 – V6 drive analysis and redesign (2)

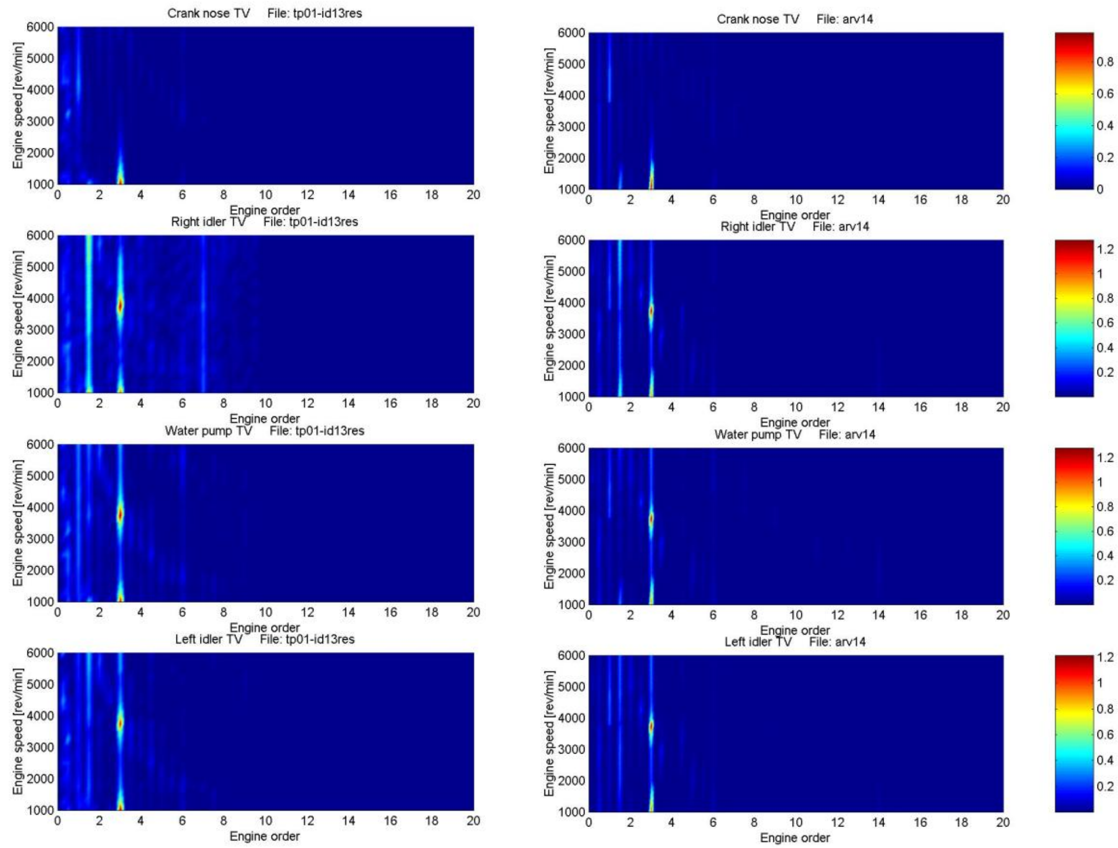
- **Initial durability tests were performed with the 8mm pitch chain drive design**
  - The chain drive components in these tests suffered high wear due the high chain loads

- **Measurements were made on the test engines to correlate the VALDYN predictions under different load conditions**

- **Measured and predicted sprocket torsional vibrations are compared across the engine speed range**
  - A strong 3rd order resonance was predicted and measured at 3800 rpm

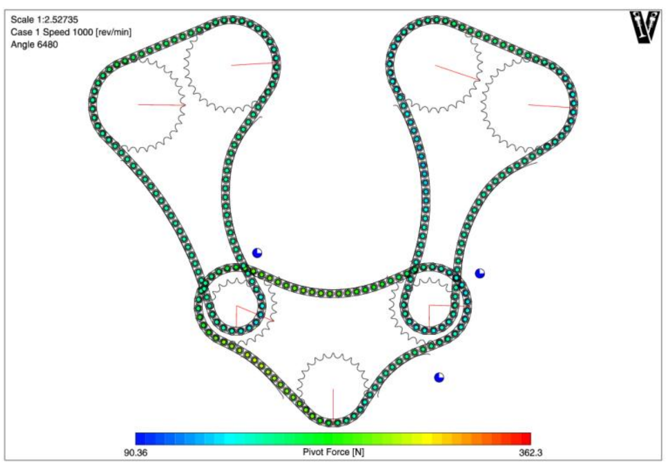
Measured Full Load

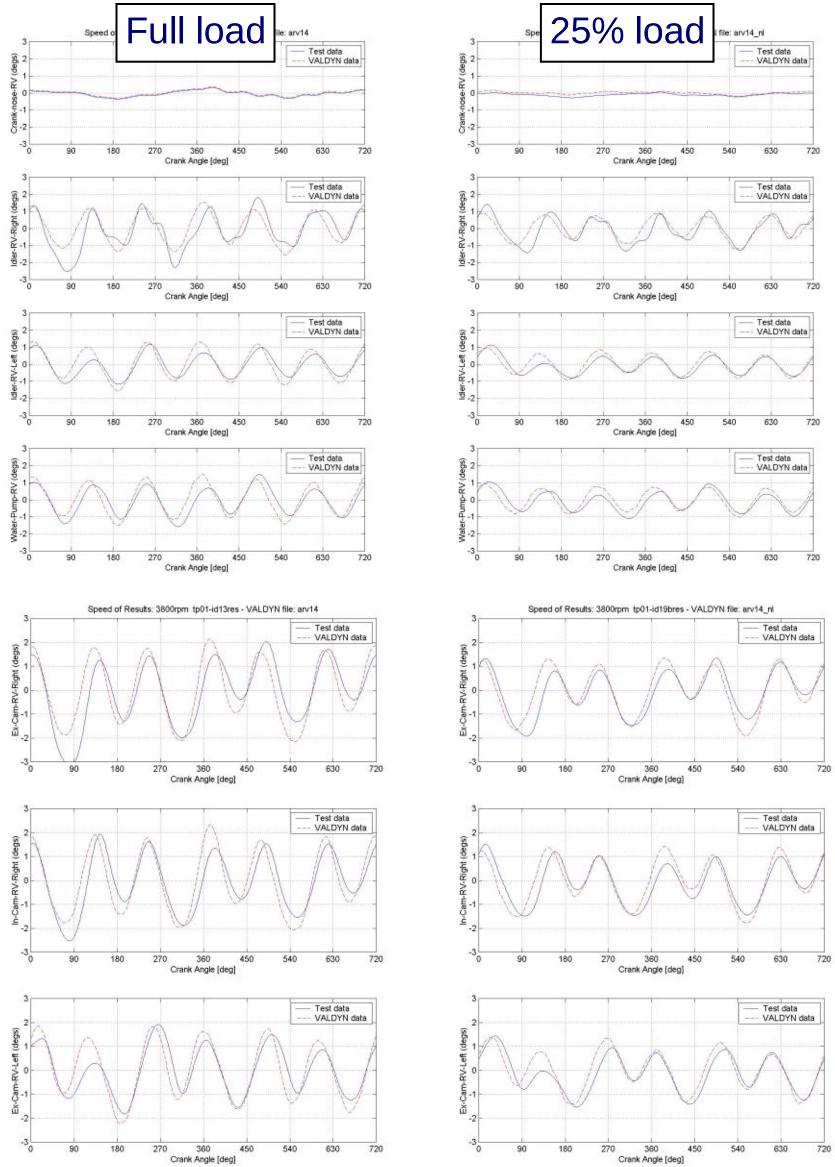
Predicted Full Load



Chain drive – Case 1 – V6 drive analysis and redesign (3)

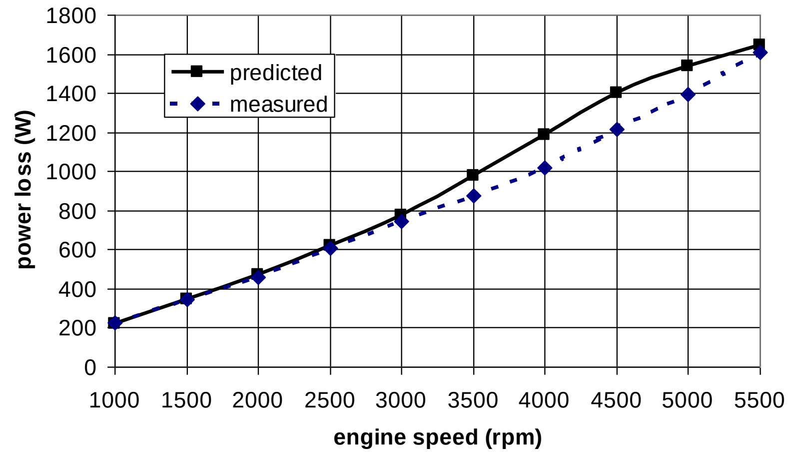
- **Excellent correlation was achieved between predicted and measured data at all sprockets under different load conditions**
  - Full load
  - 25% load
- **The significant redesign of the timing drive layout was successful in reducing the chain loads and the final design is now in production**

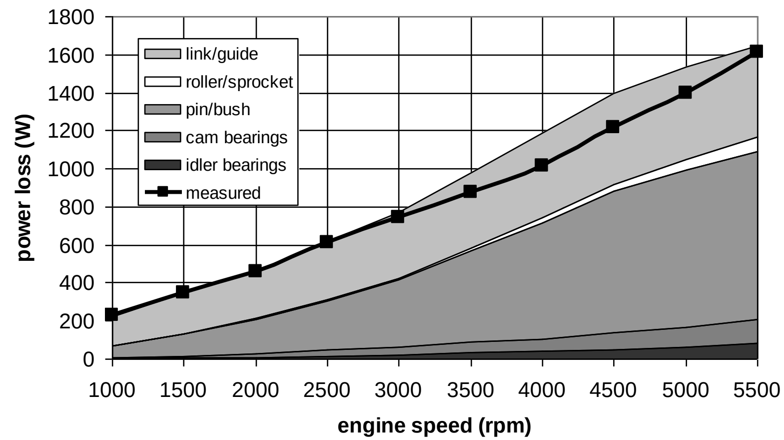




Chain drive – Case 1 – V6 drive friction analysis

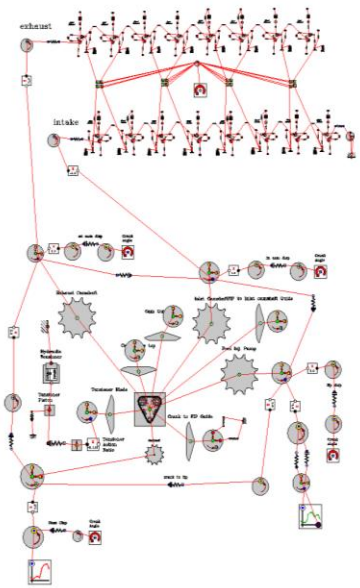
- **Timing drive friction loss was measured on the same V6 engine under motored conditions with no valve trains present**
- **The latest version of VALDYN was used to determine friction coefficients at various locations to give reasonable agreement with measured data**
  - friction coefficient at pin/bush contacts and link/guide contacts varied linearly with engine speed between 0.06 at 1000 rpm and 0.013 at 5500 rpm
  - Correlation could be improved by using non-linear variation of friction coefficient
- **VALDYN results indicate that at low speed (2000 rpm)**
  - pin/bush friction accounts for 38% of total
  - link/guide friction accounting for 55% of total

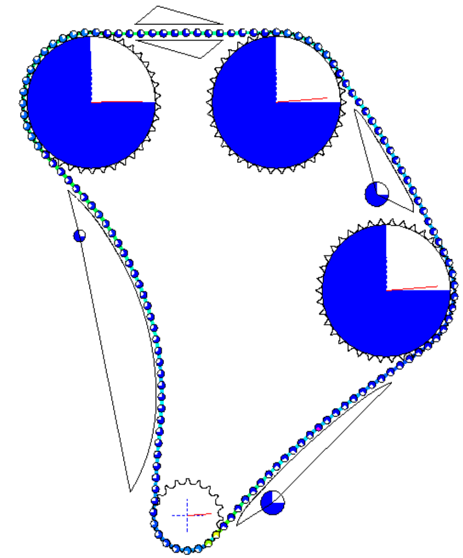


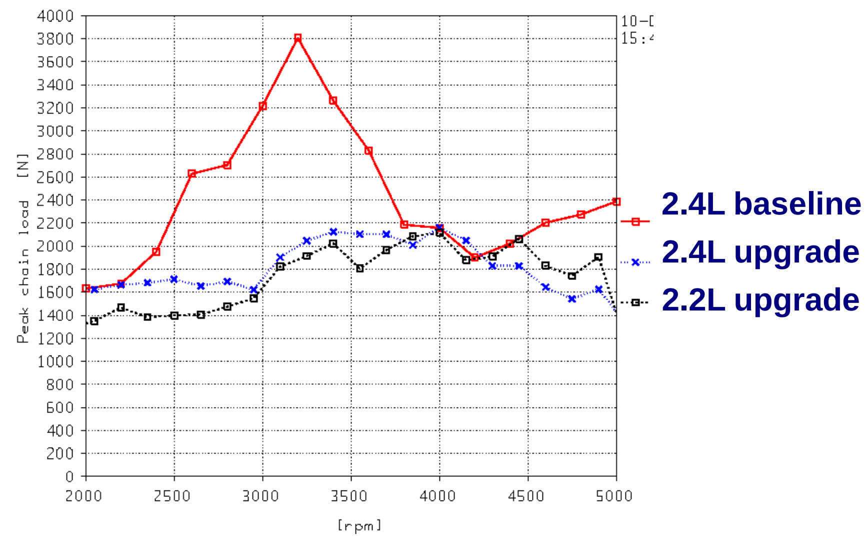


Chain drive – Case 2 - Improved design and maintained durability (1)

- **2.4L diesel engine upgrade with targets of**
  - reduced cost
  - reduced weight
- **Baseline engine had duplex bush chain timing drive**
  - required to cope with high chain forces due to system resonance excited by fuel pump
- **A different fuel pump with fewer lobes was introduced for the upgrade**
- **VALDYN was used at the concept stage**
  - Maximum allowable simplex chain load 3000 N
  - Based on predicted reduction in peak chain loads a simplex bush chain was chosen for the upgrade
  - Chain layout (guides and tensioner) was optimised in conjunction with supplier

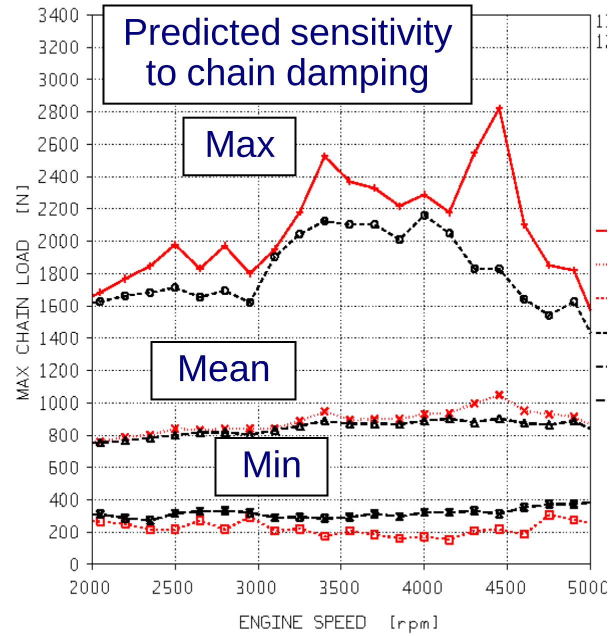


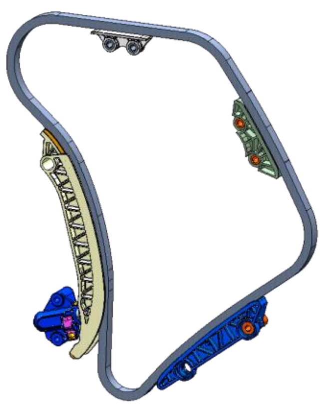


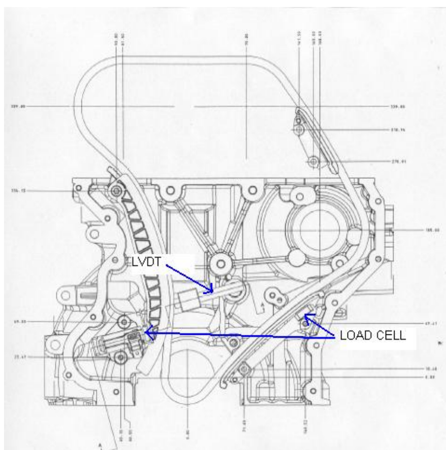


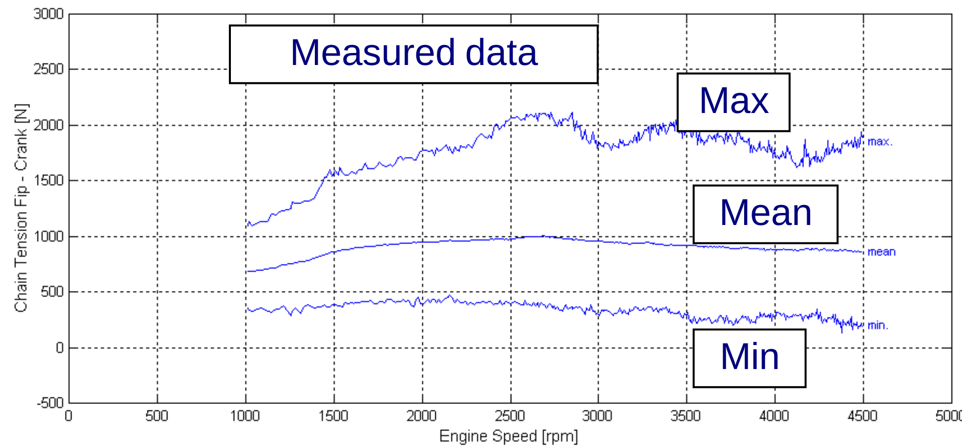
Chain drive – Case 2 - Improved design and maintained durability (2)

- **VALDYN was later used to assess sensitivity of chain loads to many parameters to prove system robustness**
- **Measurements of chain load were taken during development phase**
- **The layout chosen at the concept stage was not altered significantly and is now in production**
  - Minimised development costs
  - Significant component cost saving
  - Weight saving of 1.2 kg was achieved







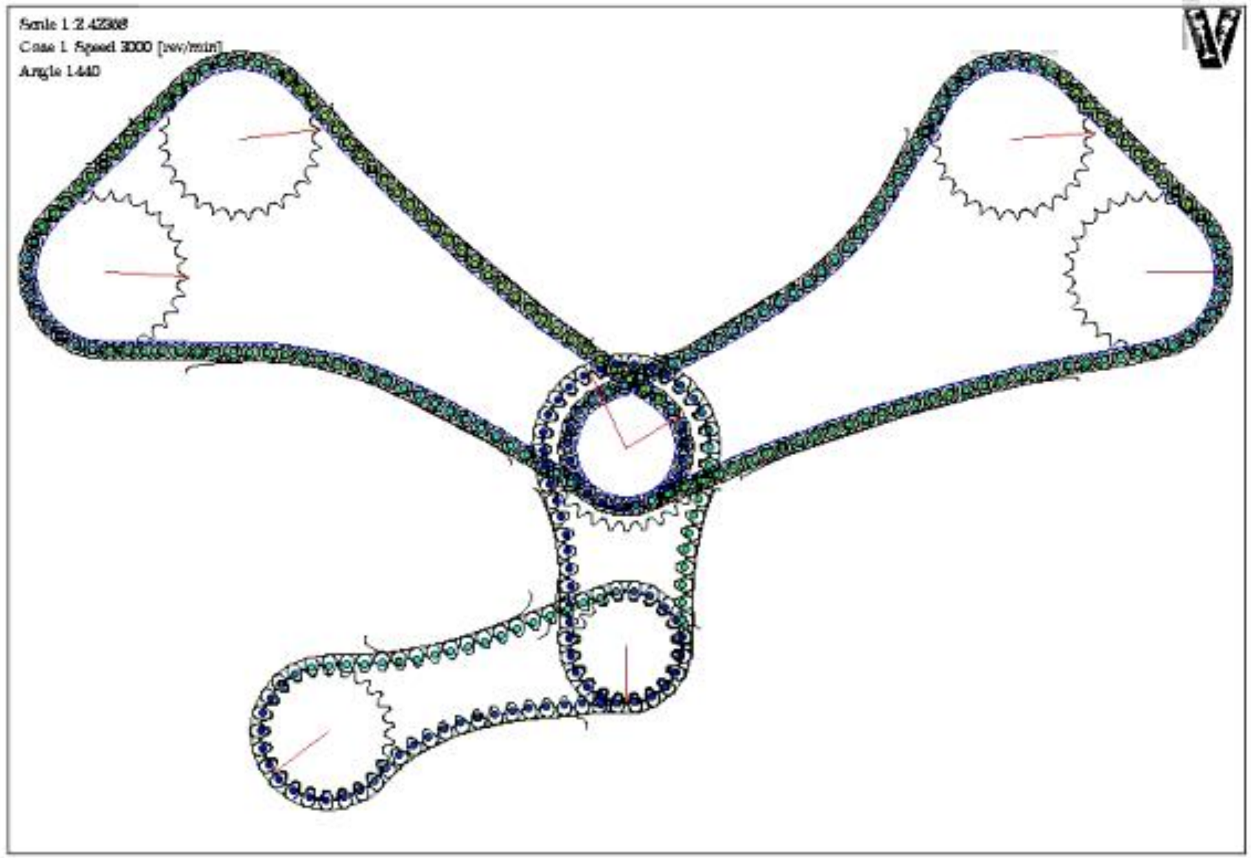


Chain drive – Case 4 – Modelling silent chains

- **VALDYN was used to optimise the chain timing drive of a V engine with respect to chain noise**

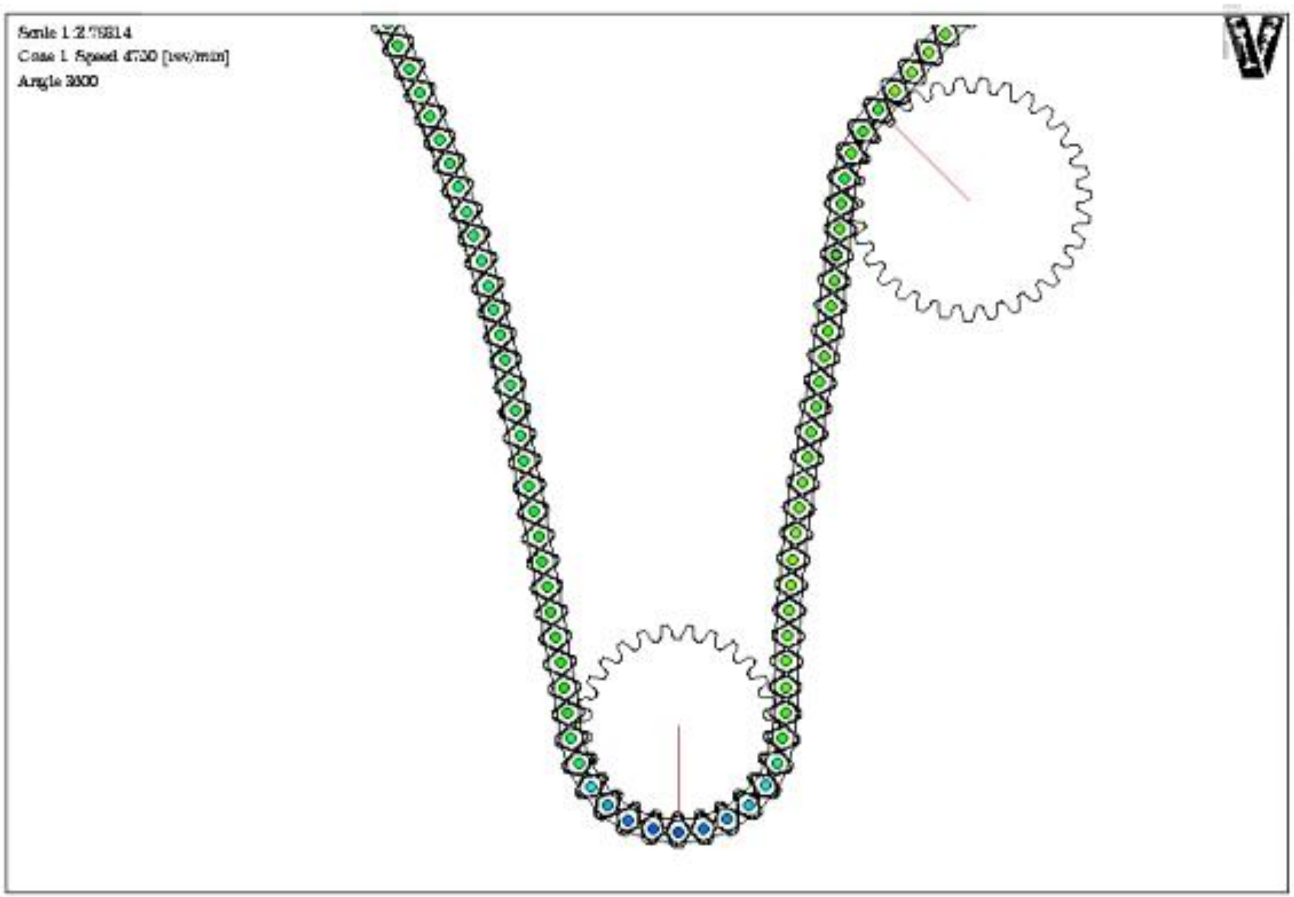
- **The timing drive included a reduction drive with a silent chain**
  - Detailed geometry of the chain links and sprocket teeth were modelled

- **Iterations with different tensioner properties, cam profiles and sprocket tooth profiles were analysed to optimise the design**
  - The noise was assessed by comparing the forces at the chain sprockets



Chain drive – Case 5 – Modelling silent chains

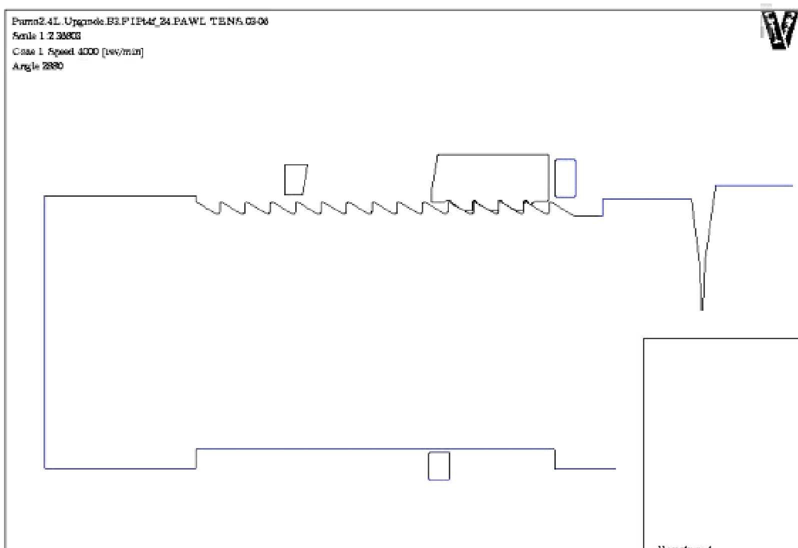
- **Double sided silent chains have also been modelled successfully**



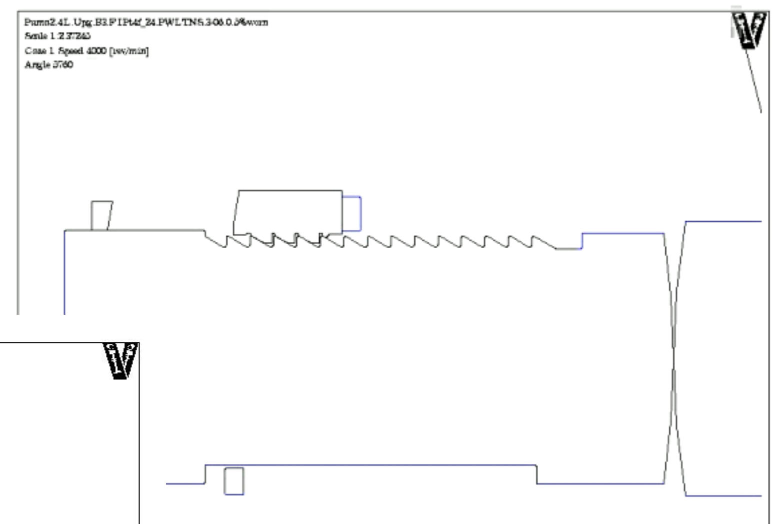
Chain drive – Case 6 – Detailed ratchet tensioner modelling (1)

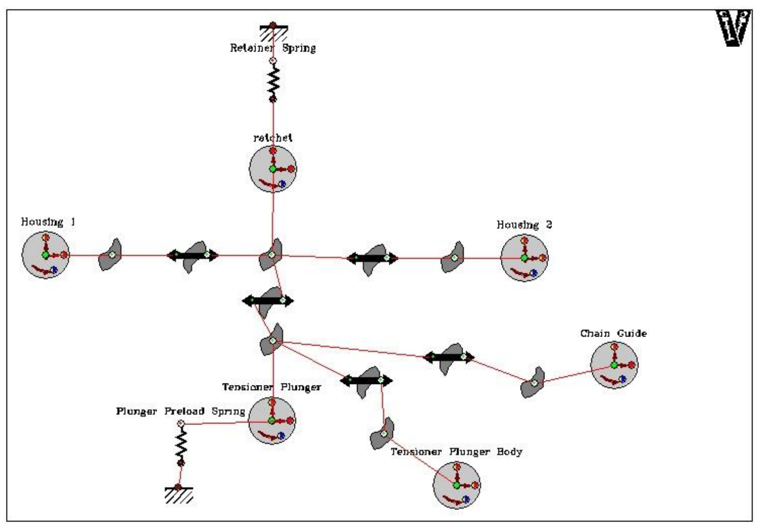
- **VALDYN was used to model the details of a new ratchet tensioner mechanism using lamina elements**
  - Prototype tensioners experienced failures due to insufficient ratchet preload
  - VALDYN was successfully used to optimise the ratchet spring preload for operation under both new and worn chain conditions

New chain



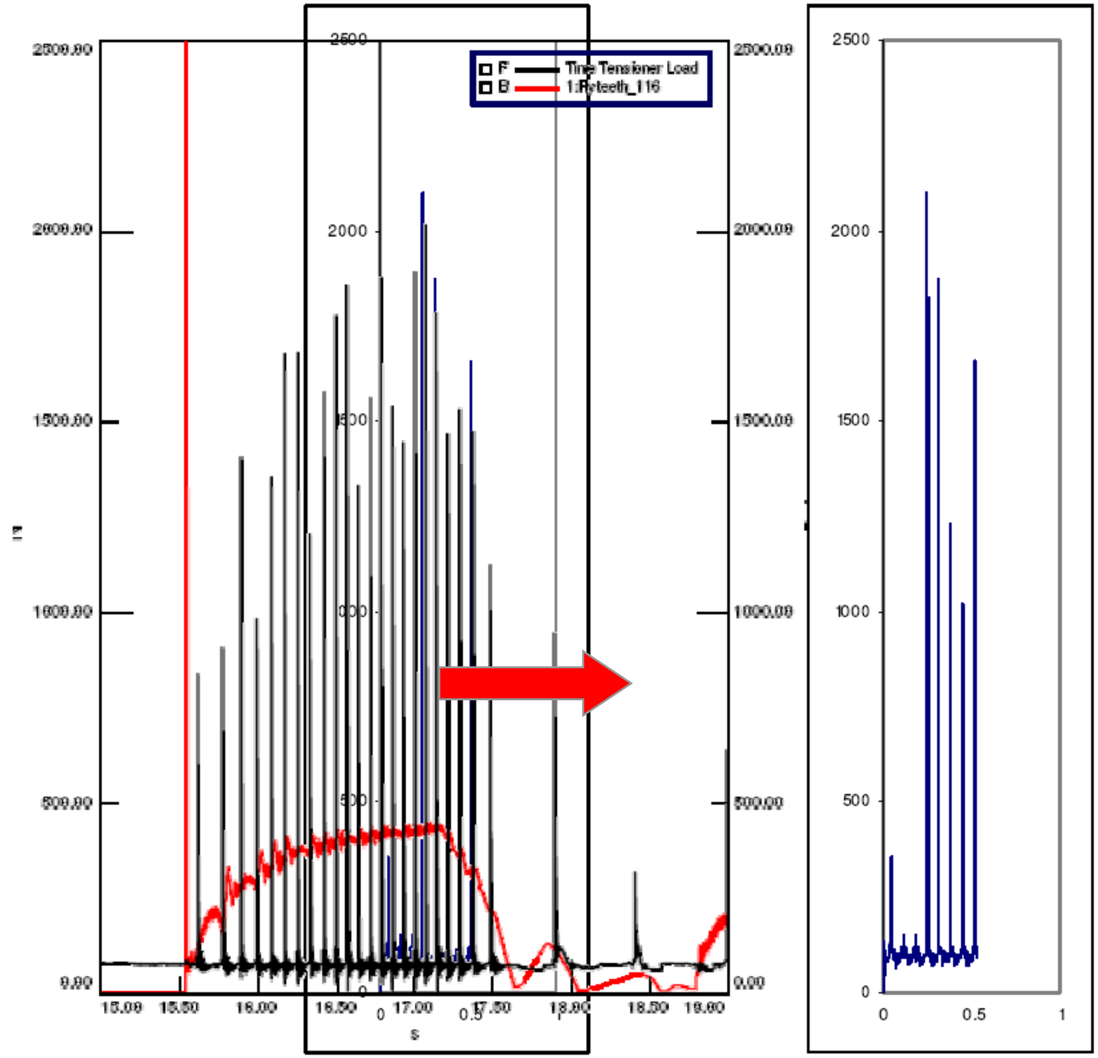
Worn chain





Chain drive – Case 6 – Detailed ratchet tensioner modelling (2)

- The VALDYN tensioner contact force predictions correlated well with measured data
- The graphs show measured and predicted tensioner piston loading during the cranking event, with no oil pressure at the tensioner
  - Black (measured piston force)
    - Peak contact force 1500-2000N
  - Red line (measured crank speed)
  - Blue data (predicted piston force) - shown overlaid with measured data and separately for clarity
    - Peak contact force 1500-2000N



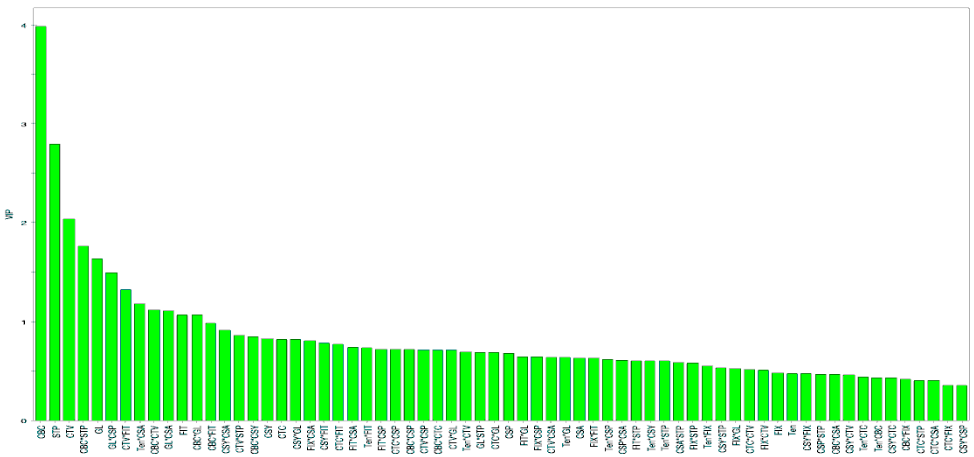
Chain drive – Case 7 – Design validation for an engine up-rate

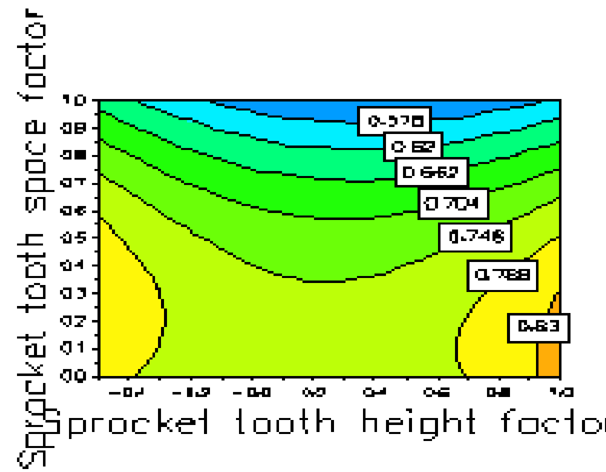
- **Ricardo were responsible for the design verification of a chain drive system as part of an engine up-rate program**
- **FMEA (Failure Modes and Effects Analysis) was used to highlight all the potential failure mechanisms of the chain drive**
  - To verify the chain drive under the new loading conditions it was necessary to prove that a 'worst case' engine build would be durable for the life cycle
  - It was impractical and prohibitively expensive to build test engines to all tolerance combinations
- **VALDYN analysis and DoE methodology were combined to provide a robust validation considering a wide range of noise factors in a practical time frame**
  - Correlated VALDYN models of the baseline engine existed from a previous study to provide confidence to the study
  - The commercial package MODDE was used for the DoE analysis

Screening Experiment to identify key design parameters → Detailed Experiment to assess the interaction of important design parameters → Predictions and optimisation

Chain drive – Case 7 – Design validation for an engine up-rate

- **Ranking plots and interaction plots were produced to highlight design parameters that were particularly important for the chain force in this drive e.g.**
  - Chain bush clearance (CBC)
  - Sprocket tooth profile (STP)
  - Crankshaft torsional vibration (CTV)
  - Fuel pump torque (FIT)





- **The maximum chain load seen, under the worst case engine conditions, was less than the fatigue limit of the chain providing confidence in the durability of the timing drive under all engine conditions**
  - The engine is now successfully in production

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- **Belt drive**
- Gear drive
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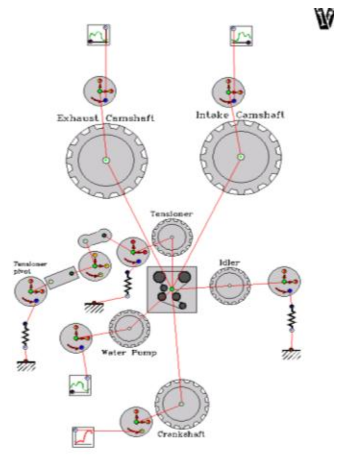
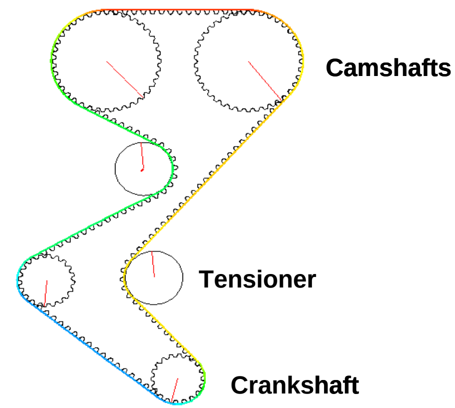
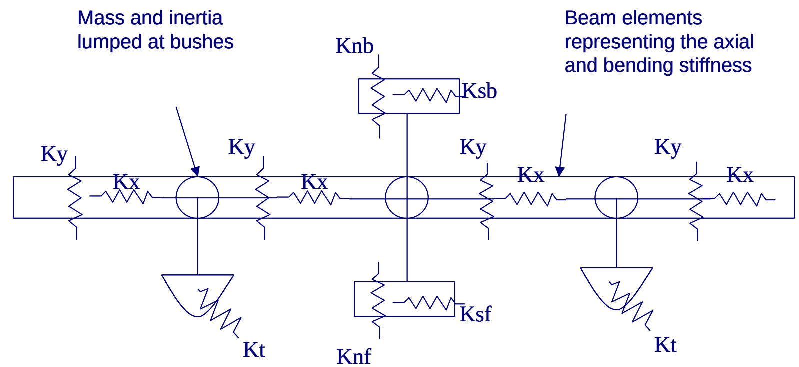
Belt drive – VALDYN capability (1)

- **VALDYN has the capability to model timing belts and has a simple user interface**
- **The latest belt element employs a geometrically non-linear representation**
  - Axial belt stiffness changes with preload
  - Bending belt stiffness dependent on the axial tension and the bending angle so the bending stiffness will change around a sprocket
- **Belt modelled as a series of beam elements to represent belt axial and bending stiffness connected by nodes representing belt mass**
- **Also attached to the nodes are stiffness elements to represent the facing and backing of the belt and belt teeth**
  - From these elements the normal forces between the belt and the pulleys are computed
  - From the friction coefficients tangential forces are computed



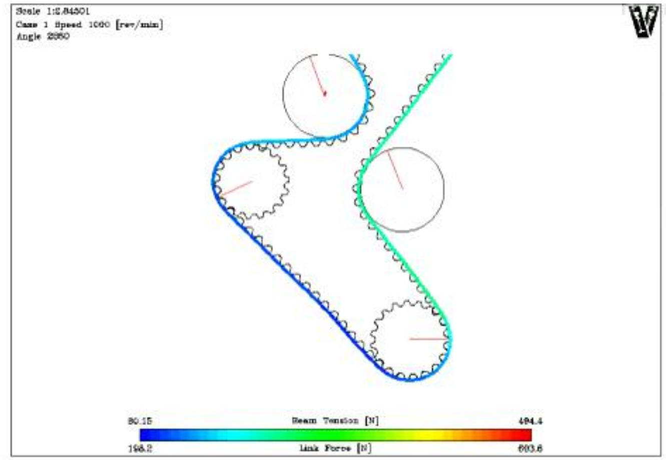




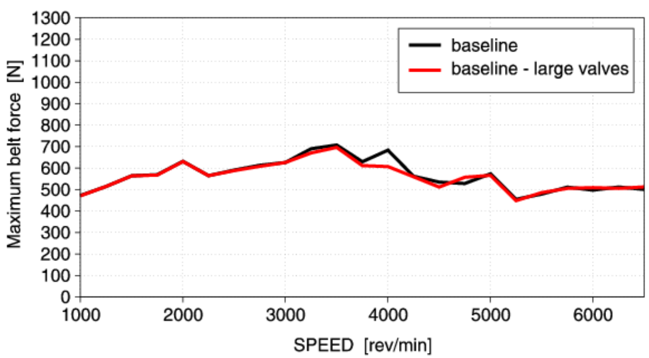
Kx	Beam axial stiffness
Ky	Beam shear stiffness
Knb	Backing normal stiffness
Ksb	Backing shear stiffness
Knf	Land normal stiffness
Ksf	Land shear stiffness
Kt	Tooth normal stiffness

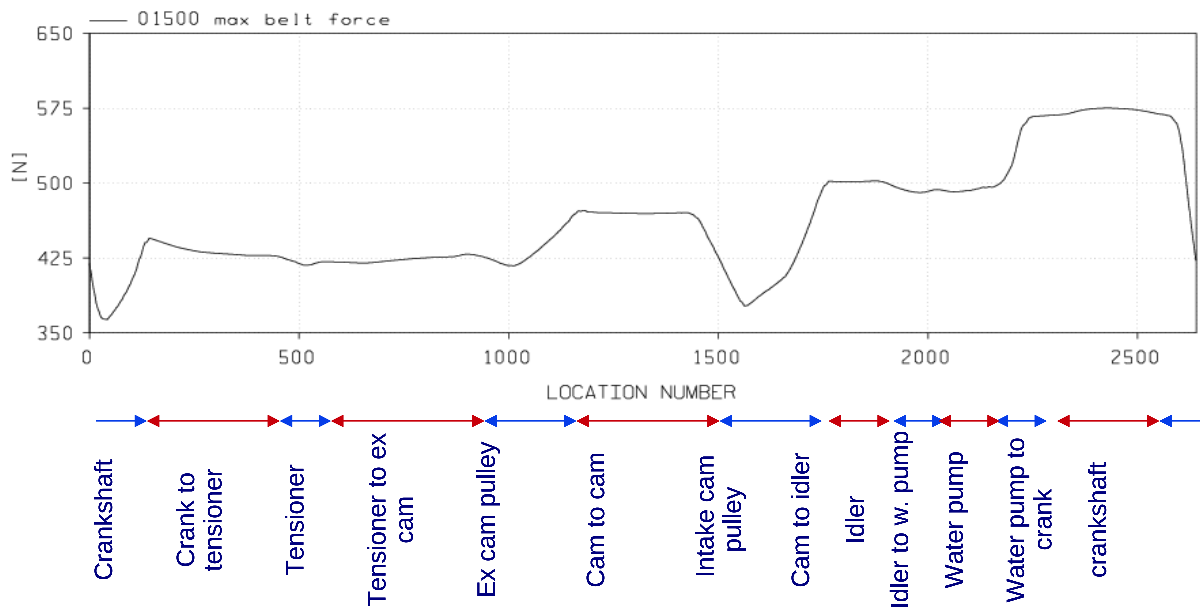
Belt drive – VALDYN capability (2)

- **Typical outputs include**
  - Belt forces plotted against location number
  - Belt forces plotted against engine speed
  - Pulley rotational displacements
  - Tensioner motion
  - Belt flap amplitudes



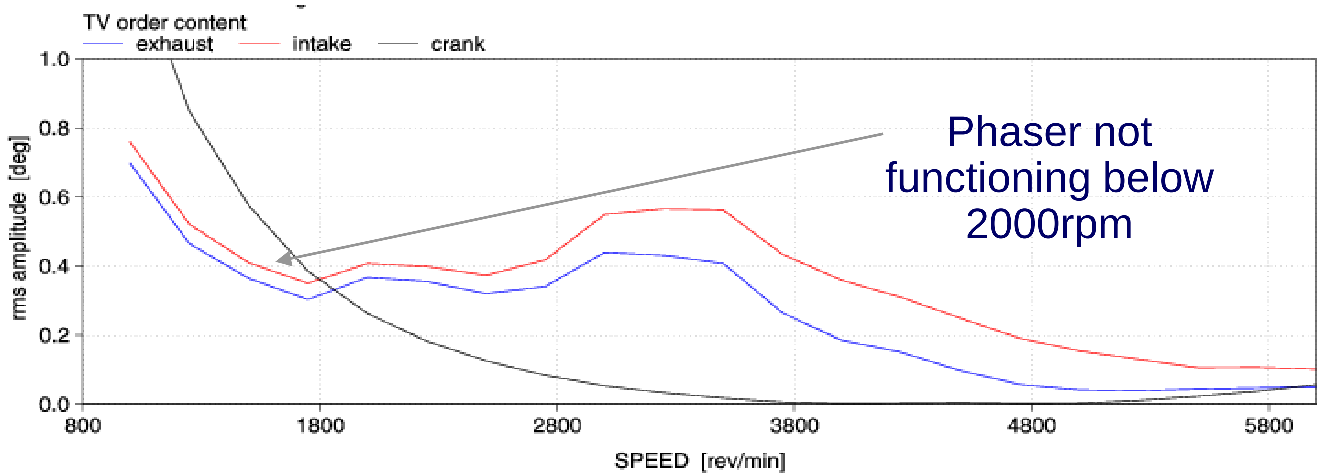
- **Animator to visualise meshing and flapping**

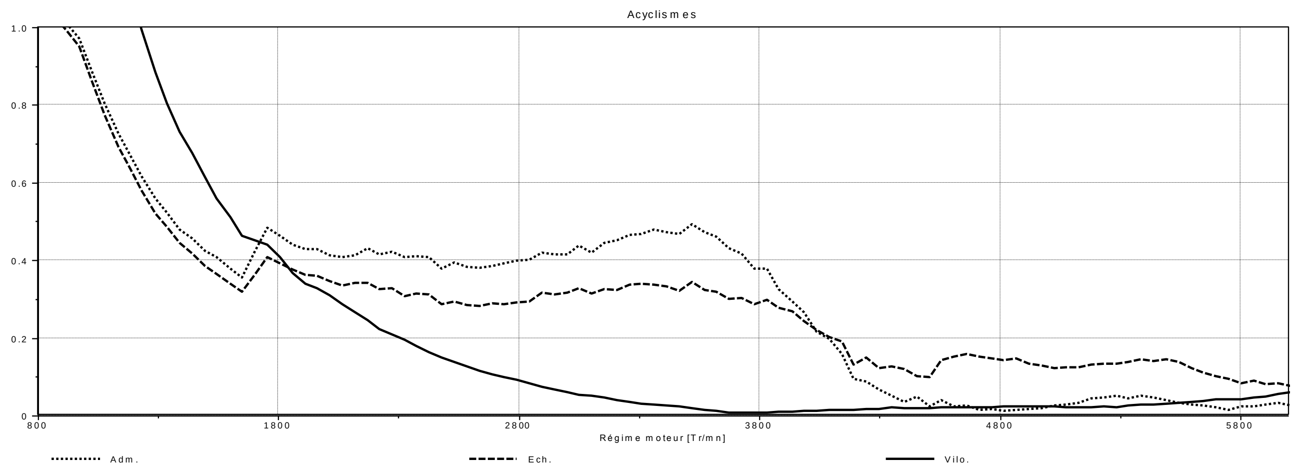




Belt drive – Correlation data (1)

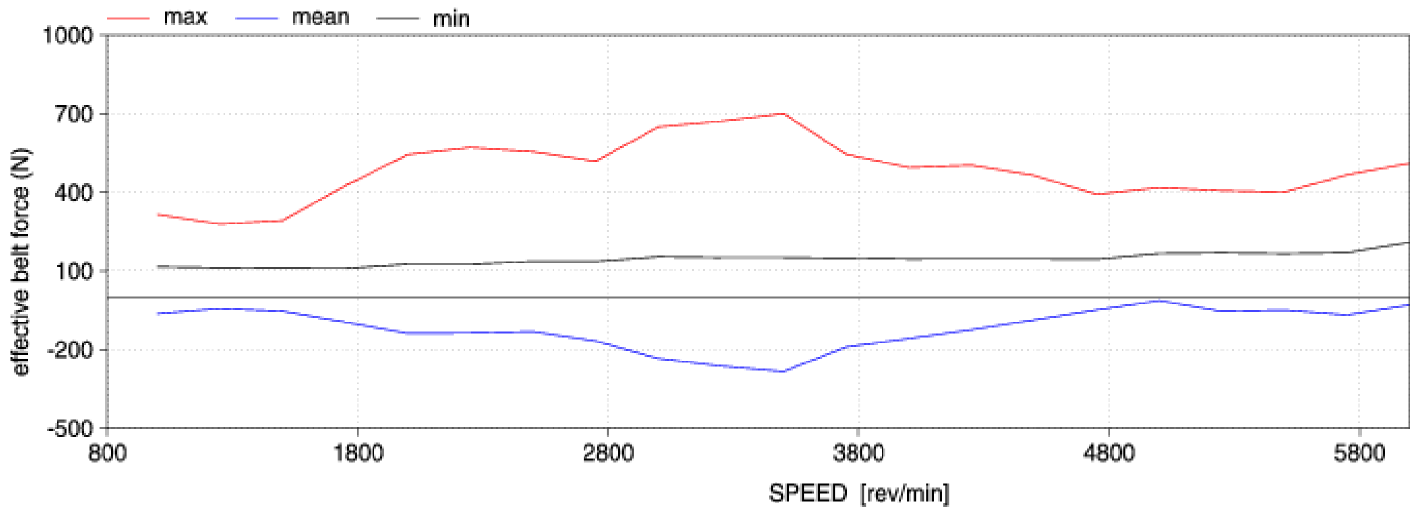
- **In-line 4 cylinder engine with cam phaser on intake cam**
- **RMS amplitude of 2nd order TVs for**
  - intake camshaft pulley
  - exhaust camshaft pulley
  - Crankshaft
- **Good agreement between measurements and predictions**

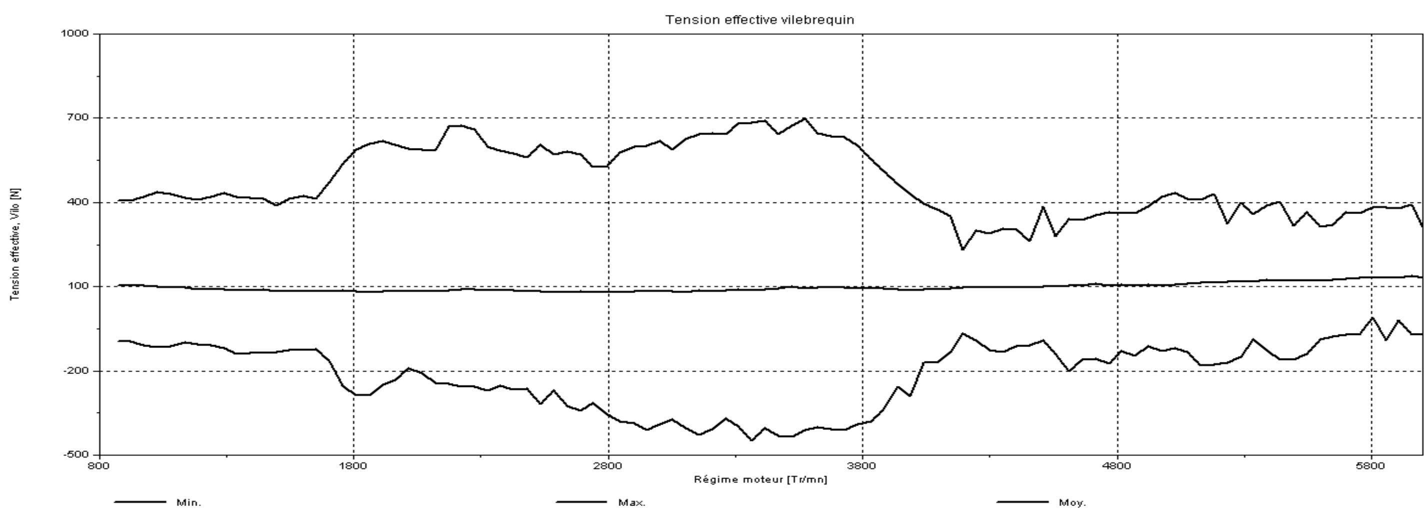




Belt drive - Correlation data (2)

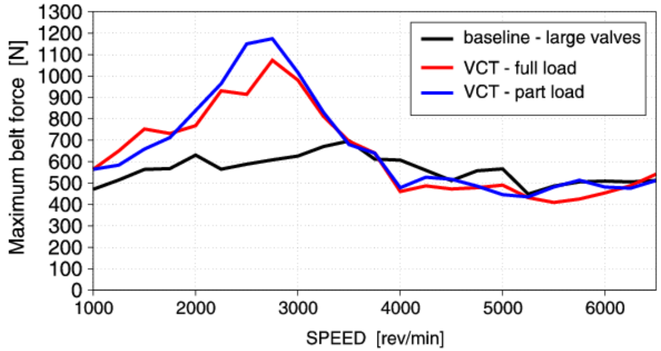
- Belt effective tension measured at crankshaft pulley
- Good agreement across speed range

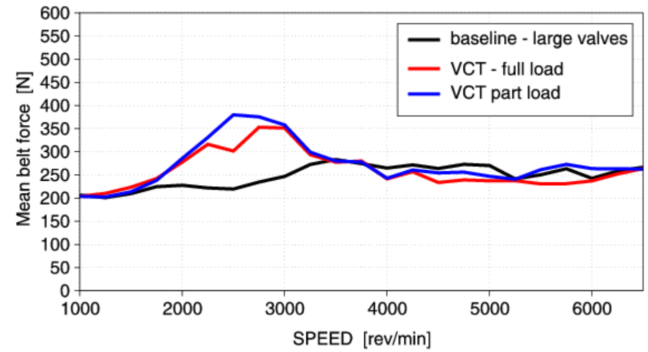


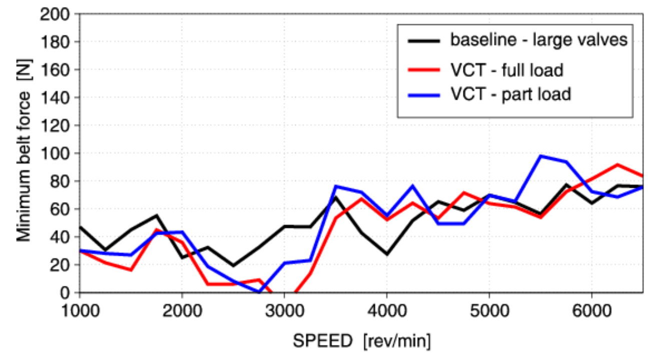


Belt drive – Case 1 – Effect of cam phasers on belt force

- **Modern gasoline engines increasingly use vane type cam phasers to adjust cam timing and so give improved balance between fuel economy, emissions and performance**
  - Maximum benefit is obtained by using phaser on both intake and exhaust systems
- **However introduction of these phasers can result in significantly increased belt forces due to**
  - increased inertia of camshafts resulting in lower timing drive natural frequency
  - unfavourable cam phasing resulting in increased excitation into timing drive
- **The effect is shown in the graphs of belt load for an in-line 4 cylinder gasoline engine**
  - Worst case belt occurs with part load phasing in 2000-3000 rpm speed range so could have significant effect on belt life
  - Minimum belt force is close to zero

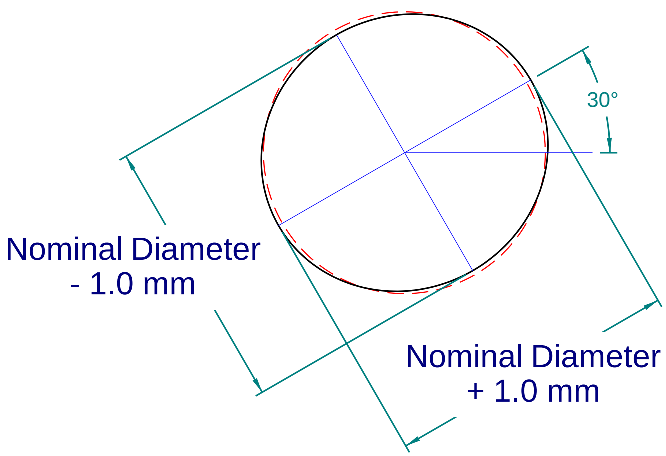


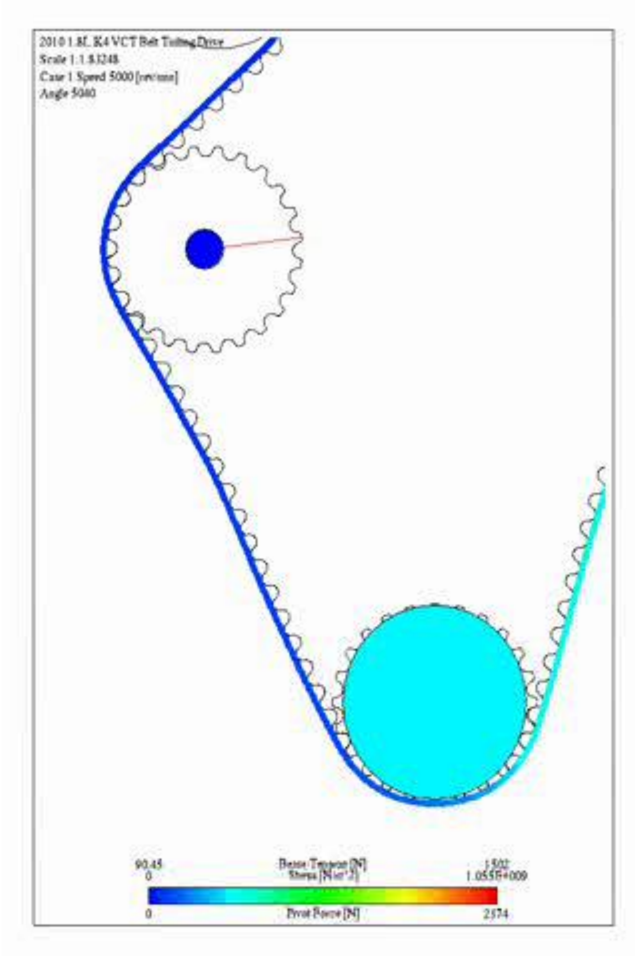




Belt drive – Case 1 – Countermeasures

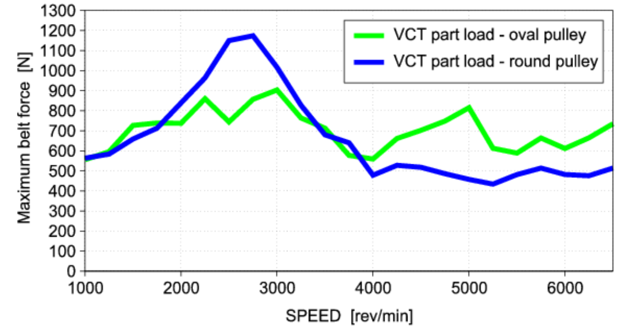
- **The problem can be addressed by**
  - increasing belt preload
  - using high strength belt
  - using camshaft TV damper
  - using additional cams on one camshaft to generate torque to oppose camshaft excitation torque
  - using non-circular “oval” crankshaft pulley
- **VALDYN can be used to investigate the potential of all of the above including the non-circular crankshaft pulley (which is now in production on Audi 2.0L FSI)**

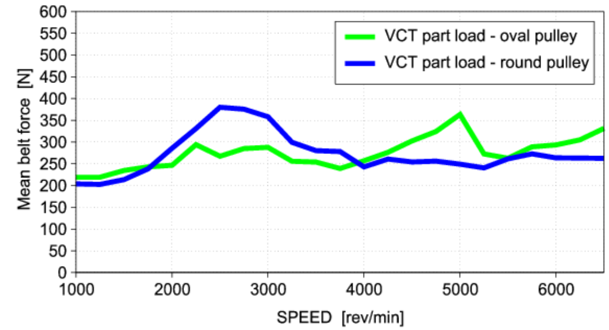


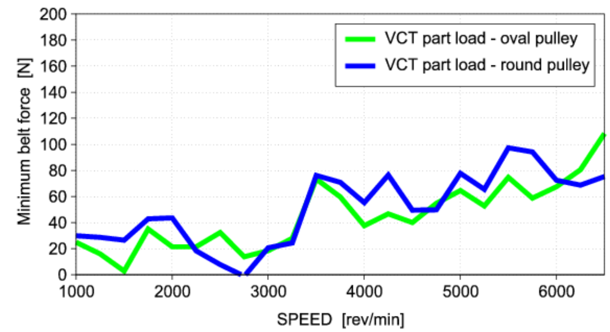


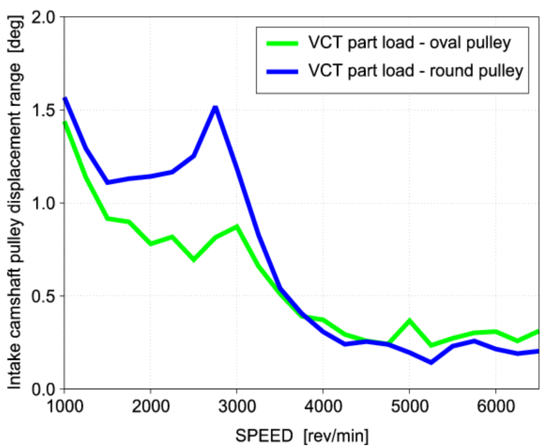
Belt drive – Case 1 – Oval pulley results

- **Graphs show the effect of an oval pulley on belt force**
  - Peak force at resonance reduced by ~25%
  - Peak forces increased at high speed
  - Minimum force positive at all times
  - INA claim this could lead to ~40% improvement in belt life
- **Sprocket displacement at resonance is also significantly removed leading to improved control of valve timing**



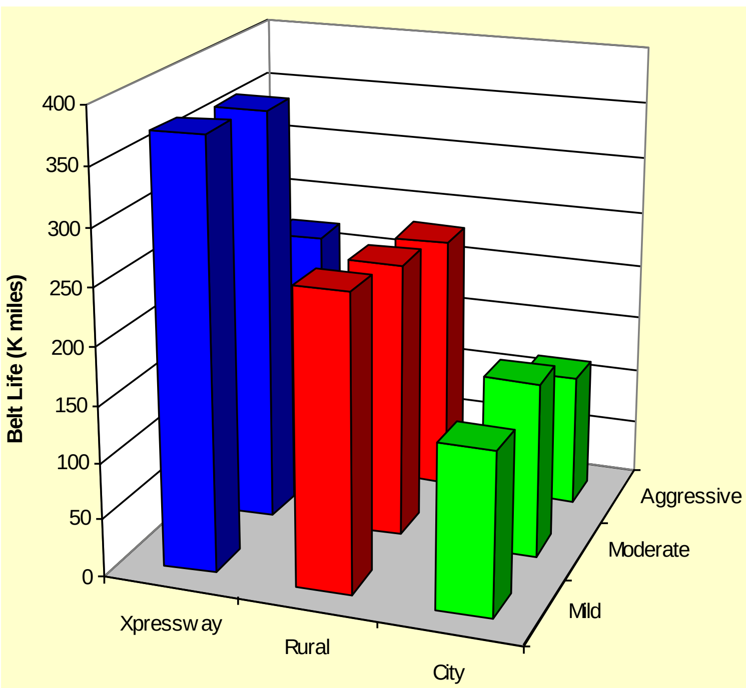


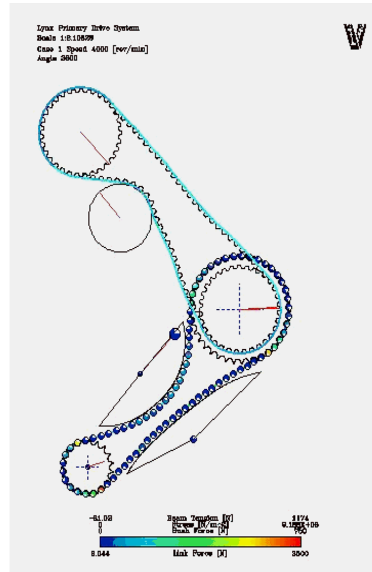


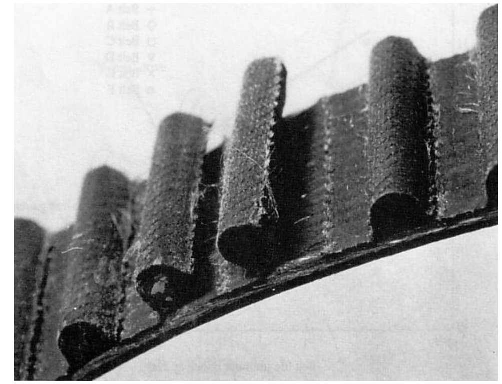


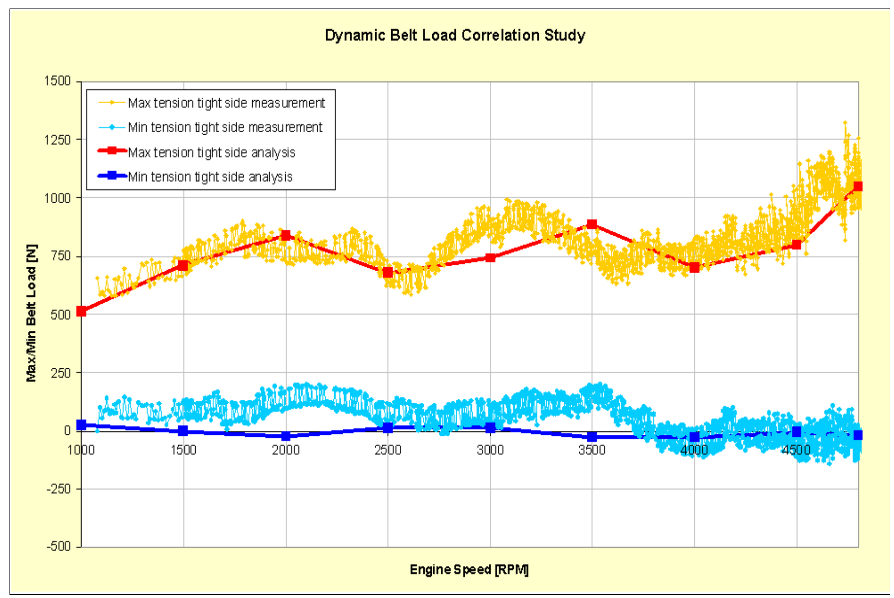
Belt drive – Case 2 – Prediction of belt life

- **Ford have used VALDYN belt model together with customer usage data to derive a belt life prediction method**
- **Belt life can be calculated based on belt forces (from VALDYN), vehicle speed, customer usage data and belt temperature**









Agenda

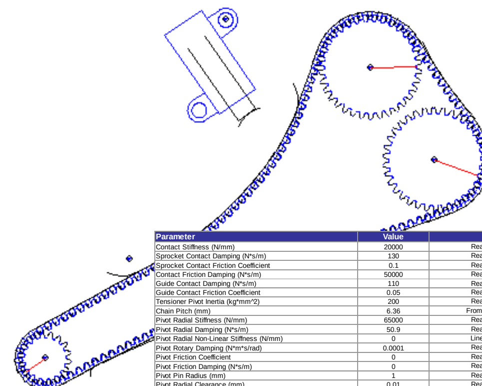
RICARDO

- Introduction
- Chain drive
- Belt drive
- Gear drive
- **Conclusions**

Conclusions – Benefits of analysis

- **Timing drive analysis using VALDYN leads to improved designs with**
  - Reduced weight
  - Reduced cost
  - Improved durability
  - Lower noise
- **Previous experience is required to maximise the benefits of analysis at concept stage**
  - Typical component stiffness values
  - Typical damping levels
  - Expected behaviour of similar systems
- **Understanding of chain drive system dynamics is now reasonably mature**
  - Analysis of belts and geared systems not far behind

Timing chain drive cassette on BMW 1.8L I4

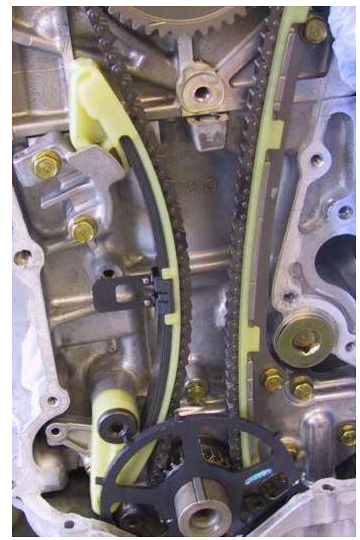


Parameter	Value	Notes
Contact Stiffness (N/mm)	20000	Reasonable Value
Sprocket Contact Damping (N*s/m)	130	Reasonable Value
Sprocket Contact Friction Coefficient	0.1	Reasonable Value
Contact Friction Damping (N*s/m)	50000	Reasonable Value
Guide Contact Damping (N*s/m)	110	Reasonable Value
Guide Contact Friction Coefficient	0.05	Reasonable Value
Tensioner Pivot Inertia (kg*mm^2)	200	Reasonable Value
Chain Pitch (mm)	6.36	From Layout Drawing
Pivot Radial Stiffness (N/mm)	65000	Reasonable Value
Pivot Radial Damping (N*s/m)	50.9	Reasonable Value
Pivot Radial Non-Linear Stiffness (N/mm)	0	Linear Model Used
Pivot Rotary Damping (N*m*s/rad)	0.0001	Reasonable Value
Pivot Friction Coefficient	0	Reasonable Value
Pivot Friction Damping (N*s/m)	0	Reasonable Value
Pivot Pin Radius (mm)	1	Reasonable Value
Pivot Radial Clearance (mm)	0.01	Reasonable Value
Maximum Lamina Interference (mm)	1.5	Reasonable Value
Number of Links	134	From Layout Drawing
X Ordinate of Right-Hand Pivot	3.17	Calculated from pitch
Y Ordinate of Right-Hand Pivot	0	Calculated from pitch
Mass of Even Link (kg)	3.219	Assumed from Previous Report
Mass of Odd Link (kg)	3.26	Assumed from Previous Report
Inertia of Even Link (kg*mm^2)	0.54	Assumed from Previous Report
Inertia of Odd Link (kg*mm^2)	0.55	Assumed from Previous Report
Camshaft Sprocket Radius (mm)	34.41	Sprocket_16.mcd
Crankshaft Sprocket Radius (mm)	17.279	Sprocket_16.mcd

Conclusions – Expected future developments in design (1)

- **Lighter chains to reduce weight, friction and noise**
- **Increased use of silent chains for low noise**
- **Increased use of flexible guides**
- **Resurgence in use of belt drives**
  - Significant improvements in belt durability mean that some engines now have belts fitted for life
  - Belts have potential for lowest friction and noise
- **Use of camshaft dampers, contra-cams and oval sprockets/pulleys to reduce chain/belt forces**
  - Particularly in systems with cam phasers

Timing belt with oval crank pulley on AUDI 2.0L I4 FSI

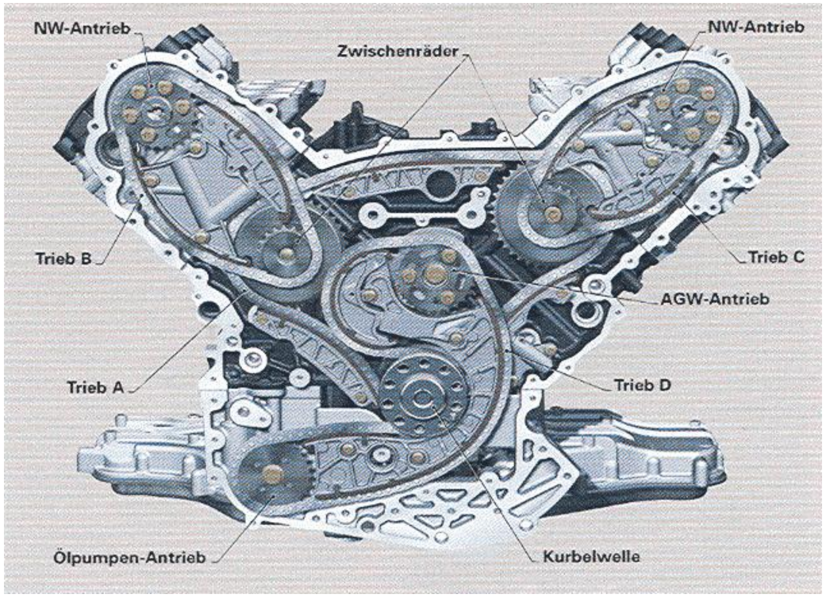


Silent chain with low cost tensioner on Honda 1.3L I4

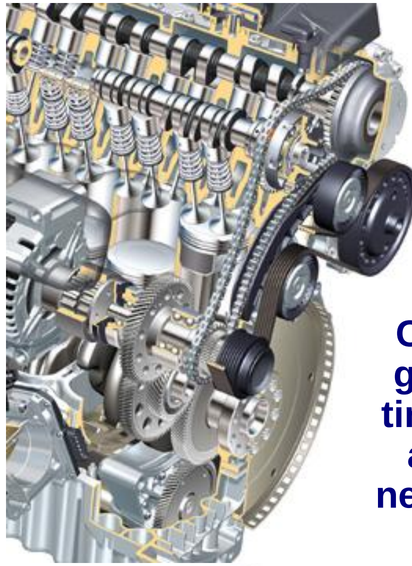
Simplex roller chain and cam/cam gears on BMW 5.0L V10

Conclusions – Expected future developments in design (2)

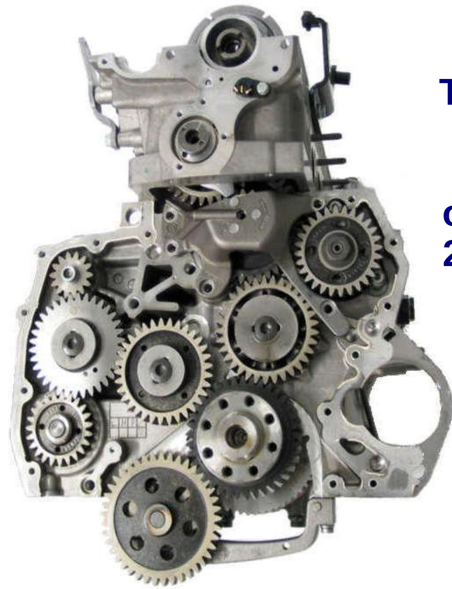
- **Use of more complex drive layouts (possibly involving gears and chains) to improve package/durability in particular applications**
  - Audi V engines
  - Volvo I6
  - VW TDI engines



Layout for rear timing drive of new Audi V6 TDI



Combined gear/chain timing drive at rear of new Volvo I6



Timing gear drive on VW 2.5L I5 TDI

Thank you for your attention
ありがとうございました

Any Questions?
どうぞご質問を